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INTEGRATED SURFACE AND GROUNDWATER QUALITY ASSESMENTS IN KARST REGIONS OF KENTUCKY

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Recent groundwater quality studies in Kentucky's karst regions have integrated surface- and ground-water quality assessment approaches to better define the nexus between the two flow systems. Surface and ground water are conjunctive systems, no more directly so than in karst terranes. Surface-water assessments (§305b report) in the well-developed karst areas, such as the sinkhole plain and the Bluegrass regions, are limited due to a relative lack of flowing surface streams. Particularly in the sinkhole plain of south-central Kentucky, karst spring basins represent large areas of contribution to the Green River that are un-assessed for water quality. Subsurface streams that drain these basins can only be assessed via their discharges to surface waters at discrete springs. Any adequate strategy for assessing these flows must meet the requirements for surface-water assessment protocols.

An integrated approach attempts to address the deficiencies of inadequately assessed "stream segments" and provide needed information on spring conditions relative to non-point source impacts to both surface water and ground water in Kentucky. Such assessments have implications relative to listing and de-listing springs as water bodies in the 305(b)/303(d) integrated report, TMDLs, watershed planning, and the availability of grant funds (e.g. §319(h)) for watershed projects in these areas. Two separate study areas in the Kentucky River and Green River basins served as pilot projects for this holistic watershed approach. Water-quality samples (including major ions, nutrients, TOC, TSS, TDS, pH, alkalinity, metals, VOCs, and pesticides) were collected monthly for one year from each spring. Total coliform and E. coli bacteria samples were also collected monthly from May through October. Of the ten springs assessed in the Green River basin, nine springs were "Not Supporting" for Primary Contact Recreation (PCR), and one spring was "Partially Supporting" for PCR. Five of these springs were "Fully Supporting" for Aquatic Life Use; the other five springs were "Partially Supporting." In the South Elkhorn watershed, 18 springs were found "Not Supporting" PCR, and three springs were "Fully Supporting" PCR. Aquatic Life Use was not determined for springs in the South Elkhorn watershed.

Comparison of hydrologic maps developed using dye-trace data to the USGS 11- and 14-digit Hydrologic Unit Code (HUC) boundaries indicates that a significant amount of mapped karst groundwater basins deviate from hydrologic boundaries based on topographic divides. Accurate hydrologic mapping is necessary to calculate water budgets and in developing watershed models for TMDLs, for implementing watershed-based solutions to water quality and quantity problems, and for first responders to spills.

NOTES

THE KARST POTENTIAL INDEX FOR KENTUCKY: PROGRESS REPORT

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A karst classification method is needed for Kentucky because qualitative descriptors are inadequate to compare the relative vulnerability of karst lands. Karst has been classified by many authors. Weary and Orndorff (2001) related karst development to structure and hydraulic gradient and used GIS files of doline polygons, spring points, and cave entrances to calculate a karst density. Klimchouk and Ford (2000, p.54-64) discussed the lithologic characteristics affecting bedrock solubility and cave genesis. Most notable is their statement that "limestone with more than 20–30% clay (argillaceous limestone) forms little karst…" and that "most limestone and dolostone caves are associated with bulk purities of greater than 90%." They also mentioned the greater rate of solubility of limestone versus dolostone. Beds greater than medium thicknesses (10–30 cm) are more favorable for cave development because of the concentration of flow to comparatively few bedding planes. The absence of insoluble material (clay, silt- and sand-size quartz) from calcareous rock is widely recognized as the most important single factor promoting karstification (Klimchouk and Ford, 2000). If the rock has a significant fraction of insoluble minerals, it will not form karst because the incipient pathways become blocked with insoluble residue, inhibiting groundwater flow and further dissolution. Klimchouk and Ford (2000) considered 50 percent clayey insoluble residue as the practical limit for karst development. The Waltham and Fookes (2003) method also has similarities to the classification system proposed here. They described a five-class karst system that is based on the concept of a summation of sinkhole density, cave size, and "rockhead" relief, or local relief between a limit of grike depth and pinnacle top. We developed a linear algorithm to quantify the propensity of carbonate rocks in Kentucky to develop karst: the Karst Potential Index (KPI). We also compared the KPI to a second measure, the Karst Development Index (KDI), to test the validity of the KPI.

The first use of a linear algorithm for ranking or indexing natural systems, (Karr, 1981) was to evaluate the health of aquatic biological communities, specifically fish. Karr modified his equation from the communication theory work of Shannon and Weaver (1964). Shannon and Weaver used the linear equation to quantify various components of a discrete, noiseless signal, L_i with probability p_i , such that the composite signal L equals the sum of the components: $L = L_i p_i + L_{i+1}\, p_{i+1} + \ldots\, L_{i+n}\, p_{i+n}$. An index of biological integrity, or an index of any other natural system, can be conceptualized as analogous to a signal with two or more alternative components (Karr, 1986). Karr's Index of Biotic Integrity (IBI) is now extensively used for assessing biological integrity of streams and other biological applications (U.S. EPA, 2004).

The KDI evaluates karst geomorphologic development utilizing the presence and aerial density of karst features. All of the measures evaluated for use in the KDI were irregularly distributed because of inconsistent reporting and incomplete exploration. We used the number of sinkholes, the total area of sinkholes, and number of karst openings in the polygon. Karst openings is the count of cave entrances, combined with springs and swallow holes, because many cave entrances are former or active springs or swallow holes. The criteria utilized for the KDI were selected because of the relative uniformity of the data sets. The feature counts and feature areas were divided by the formation area and assigned a rank of 1 to 4 based on quartiles. The resulting ranks were calculated as follows:

$$KDI = 1(Sc) + 2(Ko) + 3(Sd), \text{ ranging from 6 to 24}$$

where **Sc** = sinkhole coverage/formation area: weight = 1, score range ($1 \le Sc \le 4$), **Ko** = karst openings (springs, swallow holes, and caves)/formation area: weight = 2, score range ($1 < Ko \le 8$), and **Sd** = sinkhole density (count of closed basins)/formation area: weight = 3, score range ($1 \le Sd \le 12$).

The KPI score is based on the lithology of stratigraphic units mapped on geologic quadrangle maps. The 7½-minute, 1:24,000-scale geologic maps for Kentucky have been digitized and combined into thirty-two, 30x60 minute quadrangle maps (Anderson and others, 1999). Each polygon has attributes assigned to it, which include formation code and name. We hypothesized that the KPI, based on lithology, is a predictor of karst development. We designated all rocks with greater than 50 percent insolubles as nonkarstic. The KPI scores criteria for *bedding thickness, percentage of the stratigraphic unit that is insoluble, carbonate* *grain size*, and the *percentage of the carbonate bedrock that is calcite*. Unlike the KDI, the KPI can be calculated statewide because of the complete geologic mapping coverage. The KPI is evaluated by noting the quartile into which the data fall and then noting the rank. Assignment of a significance weight is subjective, but based on the importance of each criterion as described in the literature. The rank for each criterion is then multiplied by the significance weight, and the weighted scores summed to produce the overall KPI score. A spreadsheet was used to calculate the KPI linear equation below:

$$\boldsymbol{KPI} = 4(\boldsymbol{Ir}) + 3(\boldsymbol{Bt}) + 2(\boldsymbol{Gs}) + 1(\boldsymbol{Cp}),$$

where **Ir** = percentage of insoluble rock in stratigraphic section: weight = 4, score range ($4 \le IR \le 16$); **Bt** = bedding thickness: weight = 3, score range ($3 \le Bt \le 12$); **Gs** = carbonate grain size: weight = 2, score range ($2 \le Gs \le 8$); **Cp** = calcite percentage of the carbonate rock: weight = 1, score range ($1 \le Cf \le 4$).

All of the approximately 217,000 polygons of stratigraphic units were evaluated for the presence of features from the three KDI data sets. The complete set of features occurred in 1,128 polygons. The number of polygons was further reduced by eliminating those with stratigraphic units with greater than 50 percent noncarbonate. The remaining polygons were joined according to stratigraphic unit, resulting in 57 stratigraphic polygons for which we calculated the KPI. Most of the polygons eliminated represented insoluble rocks (caprock) overlying carbonate rocks and alluvium in valleys (mantled karst). The 57 pairs were further reduced to 33 paired values by averaging the KDI of groups of different stratigraphic units with a common KPI. Averaging the KDI values for the stratigraphic units with a common KPI data further smoothed the irregular availability of data for the KDI.

The KPI and KDI were compared using STATGRAPHICS software by Statpoint, Inc. Both the 57 and 33 paired value sample sets were evaluated for distribution, equivalence of means and correlation. The 57 paired values were not normally or log normally distributed for KDI, but were normally distributed for KPI. The 33-pair data set was not found to be statistically different from a normal distribution for both indices, using the Kolmogorov-Smirnov test for both indices. The means of the 33 paired KDI and KPI are statistically different at the $\alpha = 0.95$ confidence interval. The KPI and KDI scores were then correlated. The correlation coefficient (r^2) was 0.70 for the 57-pair set when KDI was compared to KPI, and was 0.78 for the 33 paired scores. The regression equation was KPI = (1.05 KDI x + 8.66) $r^2 = 0.78$ at $\alpha = 0.95$ confidence interval.

The findings suggest that the KPI and KDI are independent measures (different means) and that the KPI is a reliable predictor of karst development as estimated by the KDI (positive correlation among stratigraphic units). The results further suggest that the KPI has merit as a predictive tool for karst development in the climatic and geologic setting of Kentucky and potentially in other areas of the Interior Low Plateaus.

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DNA ANALYSIS OF FECAL BACTERIA TO TRACE TRANSPORT OF AGRICULTURAL PATHOGENS AT CRUMP'S CAVE, KY

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A rainfall simulation experiment was performed to investigate the transport behavior of fecal-derived bacteria through shallow karst soils and through the epikarst. The experiment was conducted at Crump's Cave located just south of Mammoth Cave National Park on the Pennyroyal Plateau Sinkhole Plain of South Central Kentucky. Using a rainfall simulator, water containing 514 ppm sulforhodamine B was applied at a rate of 6.6 cm/hr for 4 hrs to 150 kg cow manure spread over a 7.5 m^2 plot on the surface. A waterfall inside the cave, predetermined to be hydrologically connected to the surface area where the manure was applied, was sampled using a tipping bucket that delivered samples to ISCO fraction collectors at 15-minute intervals. Fecal and *E. coli* MPN numbers were determined by the Idexx Colilert system.

For DNA analysis, samples were centrifuged to collect suspended material including bacteria. DNA was extracted from the sedimented material by direct lysis, and the total DNA concentration was measured by fluorometry. DNA was further characterized by quantitative Real-Time PCR (qRT-PCR) with specific primer pairs to amplify and quantify Eubacterial DNA (all bacteria) and *Bacteroides* DNA (fecal-specific bacteria) in the samples. Results of DNA analysis supported the results seen with Colilert MPN analysis for fecal bacterial contamination of the karst aquifer.

Both methods show a bimodal distribution of fecal bacteria as it infiltrated through the soil and epikarst. Fecal bacterial numbers and DNA concentrations peaked ahead of the tracer dye followed by a second peak of fecal bacteria and DNA which roughly corresponded to the dye peak. DNA analysis also revealed that a surge of non-fecal bacteria was carried along just ahead of the dye front. These data suggest that a mobile population of non-fecal bacteria in the soil was displaced by the rain event, and that the fecal bacteria followed two routes of transport through the soil and epikarst - some fecal bacteria applied to the surface reached the waterfall quickly via a pore exclusion pathway while other fecal bacteria infiltrated through soil and interstitial fluids along with the dye front. Another advantage of using DNA analysis is that PCR products from the qRT-PCR reaction may be further analyzed to identify the bacteria in the fractions.

NOTES

PROCESS WATER MANAGEMENT (PWM) FOR
ACHIEVING WATER CONSERVATION MANAGEMENT (WCM)

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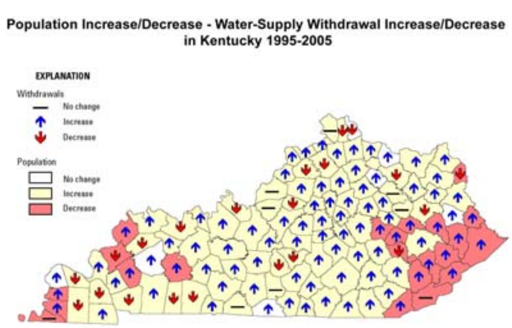
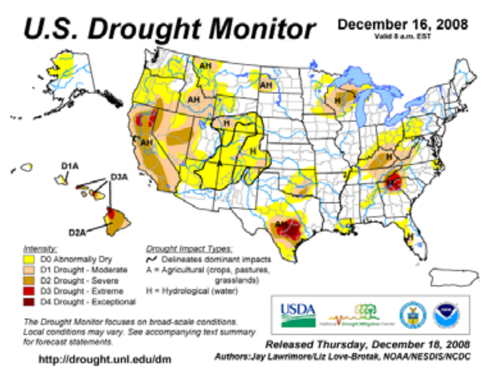
With the overall growth of both industry and population in Kentucky, the use of water by industrial, commercial, residential and public sectors continues to increase (See Chart #1). Abnormally low rainfall over the past several years has created an urgent need for water conservation management practices as surface waters and groundwater aquifers are not being replenished at a normal rate. Due to ongoing droughts and increased demand, the supply of water is less stable and predictable across Kentucky and the United States (See Chart #2). To maintain this life sustaining natural resource, an intensive, proactive focus on water use management and conservation is essential.

Chart #1-Kentucky



Source of Chart Information: USGS Website

Chart #2-United States



To assure Kentucky's future supply of water, the state must focus on its major water consumers and have an understanding of the daily demands placed on surface waters and groundwater aquifers. Inadequate or slow planning and implementation of water conservation practices could result in serious economic consequences for Kentucky and for the United States as a whole.

KPPC recognized the urgent need for Water Conservation Management (WCM) and initiated a technology-based program called Process Water Management (PWM) in 2007. PWM was designed to assist Kentucky businesses in implementing water management, pollution prevention (P2) and energy efficiency (E2) through technology advancements and improved management practices. In the early stages of this program, KPPC discovered that by implementing water management practices, water-intensive businesses could protect and conserve this natural resource. At the same time, these businesses improved their overall environmental performance through source reduction (pollution prevention), energy efficiency, and natural resource conservation. KPPC's PWM program provides Kentucky businesses proven methods for improving environmental performance and lowering operating costs.

Innovation: The Process Water Management (PWM) program is a new P2 approach. KPPC's PWM program uses activity-based costing and process mapping tied to a business metric, namely, cost reduction. The program focuses on implementing PWM projects in water-intensive industries and businesses to reduce water usage and identify potential chemical reductions and energy efficiency opportunities. The PWM program uses a seven step systems approach (adapted from the U.S. EPA's Energy Star Program) for clients to follow. KPPC provides a toolkit to client businesses to help them identify water usage, reduction opportunities, implementation plan development and ongoing program advancement.

Measurable Results: During the last two years, KPPC introduced process water management to Kentucky businesses through workshops and focus groups. Several water-intensive businesses (metal finishing & stamping, painting, office complexes and aluminum manufacturers) requested technical assistance from KPPC as a result of workshop participation. Most companies assume that water is a relatively inexpensive component of their operations and not worthy of a significant management effort. However, through education the companies learned that water costs only begin at the meter and that additional, potentially significant costs accumulate through the aqueous operational processes and waste water treatment prior to effluent discharge. With minimum initial investments, KPPC's client companies realized significant savings: 25.9M gallons of water usage; 7.4M pounds of chemicals; 20.4 MMBTUs; 121,500 KWHs; and $2.25M in total costs saved.

Transferability: KPPC's PWM program is not regional or sector specific and can be applied to nearly every organization that employs water-intensive processes. This ranges from metal finishing and food processing, to HVAC systems in large office complexes in Kentucky and across the U.S. KPPC's ultimate goal is broad-based adoption of proven PWM technologies and methodologies being demonstrated and deployed by P2 service providers to help water-intensive businesses improve P2 implementation. KPPC recommends the PWM program model for all P2 service delivery organizations nationwide. KPPC provides information on the PWM program model on its Web site, at conferences and technology forums and has published program information in trade and research journals and in newsletter articles.